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OF COLUMBIA UNIVERSITY

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SUMMARY

In the past 6 months, research has concentrated on the development and application of a surface-wave magnitude scale based on the amplitude of higher-mode Rayleigh waves. A relatively high ratio of higher mode to fundamental mode energy can be produced when an unusual combination of source depth and focal mechanism leads to poor excitation of the fundamental mode Rayleigh wave, in which case, the amplitude of the higher mode yields a more reliable estimate of the size of the event than the amplitude of the fundamental mode. Several anomalous events in central Asia, which are characterized by unusually low $M_s:m_b$ ratios and hence could be suspected to be nuclear explosions, are reclassified as earthquakes when the new, higher-mode scale, M_s^h, is employed. The focal depth and mechanism of these anomalous events apparently causes poor excitation of the fundamental mode Rayleigh wave without significantly affecting the amplitude of the higher mode. Elimination of these source related factors from traditional $M_s:m_b$ discriminants is an essential tool for reliable discrimination between earthquakes and nuclear underground tests.

M sub s : m sub b

I. STATION MAINTENANCE

The high gain station at Ogdensburg, New Jersey has been maintained in constant operation. Approximately 90 photographic seismograms are acquired each week in addition to a magnetic tape once per three weeks. These data are forwarded to the Albuquerque Seismological Center and a copy of the tape is stored in the Lamont Data File. The displacement outputs of the Geotech long-period seismometers are recorded on 2" per hour analogue chart recorders as are the outputs from the four quartz-tube strainmeters. We are in the process of transferring the seven chart records to a multichannel 3" per hour recorder which presently records data from two new wire strainmeters.

The routine operation of the observatory has required two full time technicians in the past. From October 1975 we have operated the station with one technician (M. Connor) and have discontinued recording seismic data from levels others than the -560 m level of the mine in which the observatory is located.

The digital recording of the long-period data has been interrupted on a number of occasions by electronic malfunction of the Astrodata recorder. This is now maintained by the Albuquerque Seismological Center who have arranged on site repairs when required.

II. RESULTS OF THE DATA ANALYSIS

A. Higher modes as an aid to seismic discrimination

A paper describing the application of a surface wave magnitude scale based on the amplitude of higher-mode Rayleigh waves to the discrimination of anomalous earthquakes from underground nuclear explosions has been completed and accepted for publication in the Bulletin of the Seismological Society of America (Forsyth, 1976). By using the new higher-mode scale, M_s^h, several

anomalous events in central Asia reported by other investigators were shown to be normal earthquakes. The conclusions based on the higher modes were confirmed in a number of cases by the observation of long-period (40 to 60 s) fundamental mode signals at the high-gain long-period station at Chiang Mai, Thailand. A relatively high ratio of higher mode to fundamental mode energy can be produced when an unusual combination of source depth and focal mechanism leads to poor excitation of the fundamental mode Rayleigh wave, in which case, the amplitude of the higher mode yields a more reliable estimate of the size of the event than the amplitude of the fundamental mode. Several anomalous events in central Asia, which are characterized by unusually low M_s:m_b ratios and hence could be suspected to be nuclear explosions, are reclassified as earthquakes when the new, higher-mode scale, M_s^h, is employed. The focal depth and mechanism of these anomalous events apparently causes poor excitation of the fundamental mode Rayleigh wave without significantly affecting the amplitude of the higher mode. Elimination of these source related factors from traditional M_s:m_b discriminants is an essential tool for reliable discrimination between earthquakes and nuclear underground tests.

There are three primary cases in which a relatively high ratio of higher mode to fundamental mode energy will be generated at the source. 1) The earthquake may be below the depth at which the fundamental mode is excited efficiently, yet still be sufficiently shallow to excite higher modes within the crustal wave guide. 2) For certain focal mechanisms, fundamental mode Rayleigh waves will be excited only weakly if the earthquake occurs at a depth corresponding to a zero crossing in displacement or stress versus depth for the wave. Zero crossings for the higher modes are generally not at the same depths, so if the amplitude of the fundamental mode is reduced by this effect,

the higher modes may be undiminished. 3) Except for sources very near the surface, the azimuthal radiation pattern for higher modes may differ from the fundamental modes. At azimuths corresponding to a node in the fundamental mode radiation pattern there may appear to be a relatively large amount of higher mode energy. Although each of these three mechanisms for producing a large ratio of higher mode to fundamental mode energy is frequency dependent, they can affect a range of frequencies broad enough to significantly change the appearance of the seismogram. All three mechanisms involve reducing the amplitude of the fundamental mode rather than increasing the absolute amplitude of the higher modes. Thus, when the higher/fundamental ratio is large and the surface wave magnitude based on fundamental mode Rayleigh wave amplitudes is anomalously low compared to the body wave magnitude, a more reliable estimate of seismic moment or surface wave magnitude may be obtained from the amplitudes of the higher modes.

As one of the primary applications of an improved magnitude scale will be to aid in discrimination between earthquakes and underground explosions, the higher mode scale (M_s^h) is designed to be equivalent to the fundamental mode scale (M_s) for a near-surface focus event. The scale now commonly accepted for Asian events (Marshall and Basham, 1972; Conference of the Committee on Disarmament, 1972) is of the form

$$M_s = \log A + B' (\Delta) + P(T) \tag{1}$$

where A is the maximum amplitude (nm) of the vertical component of ground motion in the Rayleigh wave train, T is the period of the wave of maximum amplitude, P(T) is the period correction which depends on the propagation path and $B'(\Delta)$ is a distance normalizing term that corrects for the effects of geometric spreading, scattering and absorption of the propagating surface wave. P(T) is assigned value

0.0 at the arbitrary reference period of 20s.

To equalize M_s and M_s^h, it is necessary to know the relative amplitudes of the two modes. At the surface, the excitation function reduces to a simple form with only those terms proportional to the horizontal displacement remaining. The amplitude of the fundamental mode wave of 20s period should be approximately 7.5 times the amplitude of the first higher mode wave of 10s period for any very-near-surface focus event. The formula for M_s^h should therefore be:

$$M_s^h = \log A + B'(\Delta) + \log T/T_o + \log 7.5$$

where T is the period of the maximum amplitude A, $B'(\Delta)$ is distance correction from Marshall and Basham (1972), and T_o is the reference period of 10s. This formula should be modified if used in areas other than central Asia, because $B'(\Delta)$ and the mode correction factor, log 7.5, may vary from region to region.

The ratio of surface-to body-wave magnitude, M_s:m_b, provides one of the principal means of distinguishing earthquakes from underground explosions (eg. Evernden, 1969; Liebermann and Pomeroy, 1969). Explosions tend to be less efficient generators of surface waves, with M_s less than $[m_b - 1.5]$. In contrast, M_s for most shallow earthquakes is greater than or equal to $[m_b - 1.0]$ (Conference Committee on Disarmament, 1972). However, there are a few "anomalous" earthquakes which have explosion-like M_s:m_b ratios, or fall between the earthquake and explosion population, i.e. $[m_b - 1.0] > M_s \geq [m_b - 1.5]$, and thus are statistically indistinguishable from explosions. Examples of anomalous earthquakes in central Asia have been presented by Landers (1972), the Conference of the Committee on Disarmament (1972), Douglas _et al_. (1974) and Nuttli and Kim (1975).

The long-period, vertical component of motion for two anomalous earthquakes and an underground explosion are shown in figure 2 as recorded at the WWSSN station in Kabul, Afghanistan (KBL, Fig. 1). Locations and magnitudes are given in Table 1. The signal from event A, an earthquake in Kazakh, shown at the top of the figure, happens to be superimposed on the Rayleigh wave train from a much larger earthquake in the Tonga region. Although the high-frequency Rayleigh wave from the Kazakh event is clearly visible, it is impossible to obtain a reliable estimate of the 20s signal level of the smaller earthquake. Event A can be seen at several other stations in central Asia, but in each case, the surface waves from Tonga interfere. All of the anomalous events are small, making it difficult to measure the spectrum over a period range broad enough to avoid frequency-dependent source effects, even when there is no interfering signal. For event A, M_s has to be based on signals of period 7 to 8s, yielding an estimated magnitude of 2.9, well within the explosion population. However, as Landers (1972) pointed out, the amplitude of the higher mode arrival at about 3.4 km/s is equal to or greater than the amplitude of the fundamental mode. The revised estimate of surface wave magnitude, $M_s^h = 3.9$, places the event in the earthquake population (Table 1). Another similar event located nearby (C in Table 1) is also removed from the anomalous category by using M_s^h. The number of observations on which M_s^h is based is listed in the last column of Table 1.

Unlike events A and C, for which no long-period surface waves could be detected, event B generated 20s Rayleigh waves which could easily be measured at KBL (2nd line in fig. 2). The M_s:m_b relation for event B falls between the earthquake and explosion populations, but again, the amplitude of the higher mode restores it to the earthquake group. M_s^h also allows two of the anomalous earthquakes listed by Nuttli and Kim (1975) to be classified as normal earth-

quakes (events E and F in Table 2). Event F is unusual in that 40-to 60s period Rayleigh waves are clearly visible at the WWSSN station NDI and the high-gain, long-period station at Chiang Mai, Thailand (CHG), even though very little fundamental mode Rayleigh or Love wave signal with period less than 30s can be seen at any station. The higher mode from this event travels with a group velocity of about 3.8 km/s, in contrast to the crustal velocities observed for other events. The mantle-like velocity of the higher mode and the long-period character of the fundamental mode suggests that the earthquake occurred deep within the Himalayan crust, perhaps at a depth of 70 km or more. M_s based on the 60s period wave is about 4.0, in reasonably good agreement with M_s^h. Event D occurred in nearly the same location as event F, but was too small to generate an observable higher mode. The fundamental mode could, however, be detected at the CHG high-gain station where it was recorded with the same waveform at about half the amplitude of event F. I suggest that event D also occurred deep within the Himalayan crust and, by analogy with event F, should be assigned an M_s^h of about 3.8. Other examples of higher modes from anomalous earthquakes in the Tibetan area are presented by Tatham et al. (1975) and the effect of using M_s^h instead of M_s is shown in fig. 3.

If the higher mode magnitude scale is correct, M_s^h should be equal to M_s for very shallow earthquakes or underground explosions. Although there are as yet no known explosions within an area with a 70 km thick crust, an attempt was made to test the validity of the scale using signals from the Soviet nuclear test site in eastern Kazakh (fig. 1). One effect of a thinner crust is to reduce the period of the higher modes trapped in the crustal wave guide. As can be seen in the bottom trace in fig. 2, the maximum period of the higher mode generated by the explosion is only about 5s. M_s^h for three explosions at the site, events G, H and I in Table 2, is 0.05 to 0.15 units larger than M_s. This

discrepancy is not large and may be due to the differences in crustal structure between the test site and the locations of the anomalous earthquakes for which the scale was designed.

B. Ultra-long period studies

The long-period analogue records from OGD strainmeters, gravimeters and tiltmeters accumulated at the seismic observatory since 1960 are being searched, cataloged and reorganized. The data is in the form of strip charts and a machine has been devised to enable the rapid conversion of the analogue trace to a digital card format. The strain records are of interest in that, although they are poorly calibrated in places and possess uncertain linearity, they represent an unusually long data set. We intend to search the data for temporal changes in relative tidal admittance and to examine the ultra-long-period part of the seismic spectrum. The re-organization revealed that the quartz strain-meters have operated for 95% of the time since their installation, the missing 5% being partly by the loss of individual rolls of data which have been borrowed and not returned. Except for periods of maintenance and occasional electronic malfunction most of the existing data are usable. The strain data consist of approximately 1100 rolls of paper chart with a single ink trace written on each. During the reorganization each roll was examined for time mark consistency, calibration marks, manual adjustments and for data quality.

Some of the strainmeter data has already been digitized. A plot of 4 years of digitized data from one strainmeter is shown in fig. 4 and its stability in comparison with other high-quality instruments is shown in fig. 5. The record has been smoothed with a 48 hour Gaussian Filter to remove tides (M_2 tidal amplitude shown to scale). The record reveals two important features of the Ogdensburg strain data. There is an absence of annual thermal signals and the "drift" rate is less than 10^{-7}/year. We believe that at least some of the

observed data is affected by instrumental instability since increased strain rates follow instrumental modifications. It appears that the record may be of sufficiently low instrumental drift to comment eventually on changes of secular strain.

III. IMPROVEMENTS TO LONG-PERIOD RECORDING SYSTEMS

The Ogdensburg strainmeters have been recorded since 1960 on paper chart analogue recorders (at 2 inches per hour without filtering) and as seismograms (at ¼ inch per minute) after passing through a band-pass filter. The dynamic range of the band-pass filter is inadequate for useful studies of the Earth's free oscillations and the characteristics of the filter are insufficient to suppress 20 second surface waves relative to waves with periods between 1 minute and 1 hour. The circuit diagram of the filter is shown in fig. 6.

We intend to improve the recording system to enhance the dynamic range and accuracy of free oscillation data both from the strainmeters and the Broad-Band seismometer. Ultimately we shall record four components of strain (azimuths 29.5°, 49.5°, 132° and vertical) and three components of acceleration (the displacement outputs of Geotech N/S, E/W and vertical seismometers) on a digital recorder sampling at 5 second intervals. As an immediate step towards this goal we have introduced improved filters to replace the previous band-pass filters. The circuit diagram and output characteristics of the new filter (designed by W.E. Farrell, CIRES Boulder) are shown in figs. 6 and 7. The filters have been modified to interface with present recording equipment and have been provided with differential high-impedance inputs. Seven filters are housed in a hermetically-sealed enclosure which now acts as a distribution point for all the long-period strain and acceleration data.

During the coming year we will upgrade the displacement transducers on all seven instruments. At present these are all tuned-resonant circuit capacitative

systems which have poor stability and are difficult to calibrate. We intend to replace them with ratio-type transformer capacitive transducer electronics.

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Nuttli, O.W. and S.G. Kim (1975). Surface-wave magnitudes of Eurasian earthquakes and explosions, Bull. Seism. Soc. Am., 65, 693-709.

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TABLE 1. MAGNITUDES AND LOCATION OF ANOMALOUS EVENTS AND EXPLOSIONS

Event	Date[1]	Origin time[1]	Latitude[1]	Longitude[1]	Depth[1]	m_b	M_s	M_s^h	No. Sta.
	(d-m-yr)	(hr:min:s)	(°N)	(°E)					
A[2]	5-1-69	04:00:08.7	44.0	77.9	53	4.9	2.9	3.9	3
B[2]	12-9-69	13:41:09.0	40.1	70.7	33	4.9	3.6	4.1	3
C[2]	7-1-68	19:14:54.7	44.0	79.3	33	4.8	2.9	3.9	3
D[3]	10-24-71	08:49:04.6	28.2	87.2	44	4.8	2.8	(3.3)	
E[3]	11-24-71	08:25:24.6	38.7	73.3	33	4.6	2.8	3.6	2
F[3]	12-4-71	08:38:00.7	27.9	87.9	32	4.9	3.2	4.1	2
G	11-30-69	03:32:57.1	49.9	79.0	0	6.1	4.2	4.3	3
H	3-22-71	04:32:57.7	49.8	78.2	0	5.8	4.1	4.1	3
I	11-2-72	01:26:57.5	49.9	78.8	0	6.2	3.9	4.1	4

1. Hypocentral data from NEIC.
2. Original reference: Landers (1972)
3. Original reference: Nuttli and Kim (1975)
4. All M_s values have been recomputed to a common scale and may not be identical to original references.

FIGURE CAPTIONS

Fig. 1 Index map of source locations and WWSSN stations. Events 1-3 are listed in Table 1 and events A-I are listed in Table 2.

Fig. 2 Tracings of long-period, vertical component of records at the WWSSN station in Kabul (KBL). Traces have not been normalized and relative amplitudes are correct. Arrows indicate group velocities on each trace. Top line is from anomalous event A, 11° away; middle line is from anomalous event B, 6° away; and bottom line is from underground explosion G, 17° away. Strong arrival at about 3.0 km/s on explosion record is short-period branch of fundamental mode.

Fig. 3 M_s-m_b diagram summarizing analysis of Tibetan anomalous events. Arrows and diamonds show increase in M_s values when observations of higher-mode Rayleigh waves are included, with (+) indicating original M_s value. Arrows and open circles show increase in M_s values when observations of Love waves are included. All events are located in eastern Tibet and are described in detail in Tatham _et al._ (1975).

Fig. 4 Ogdensburg strain data with tides removed by 48-hour Gaussian filtering. M_2 tide amplitude shown.

Fig. 5 Ogdensburg secular strain compared with strain rates observed by other investigators. The Pinion Flats data when corrected for tilting of end piers exhibits considerably less annual strain. The data is presented in "years-since-installation". Strain in units of 10^{-7}.

Fig. 6 Circuit diagrams for old (bottom) and new (top) band-pass filters for strainmeter data. New filters are more stable, with flatter

response and greater dynamic range.

Fig. 7 Amplitude and frequency response of outputs from new strainmeter filter.

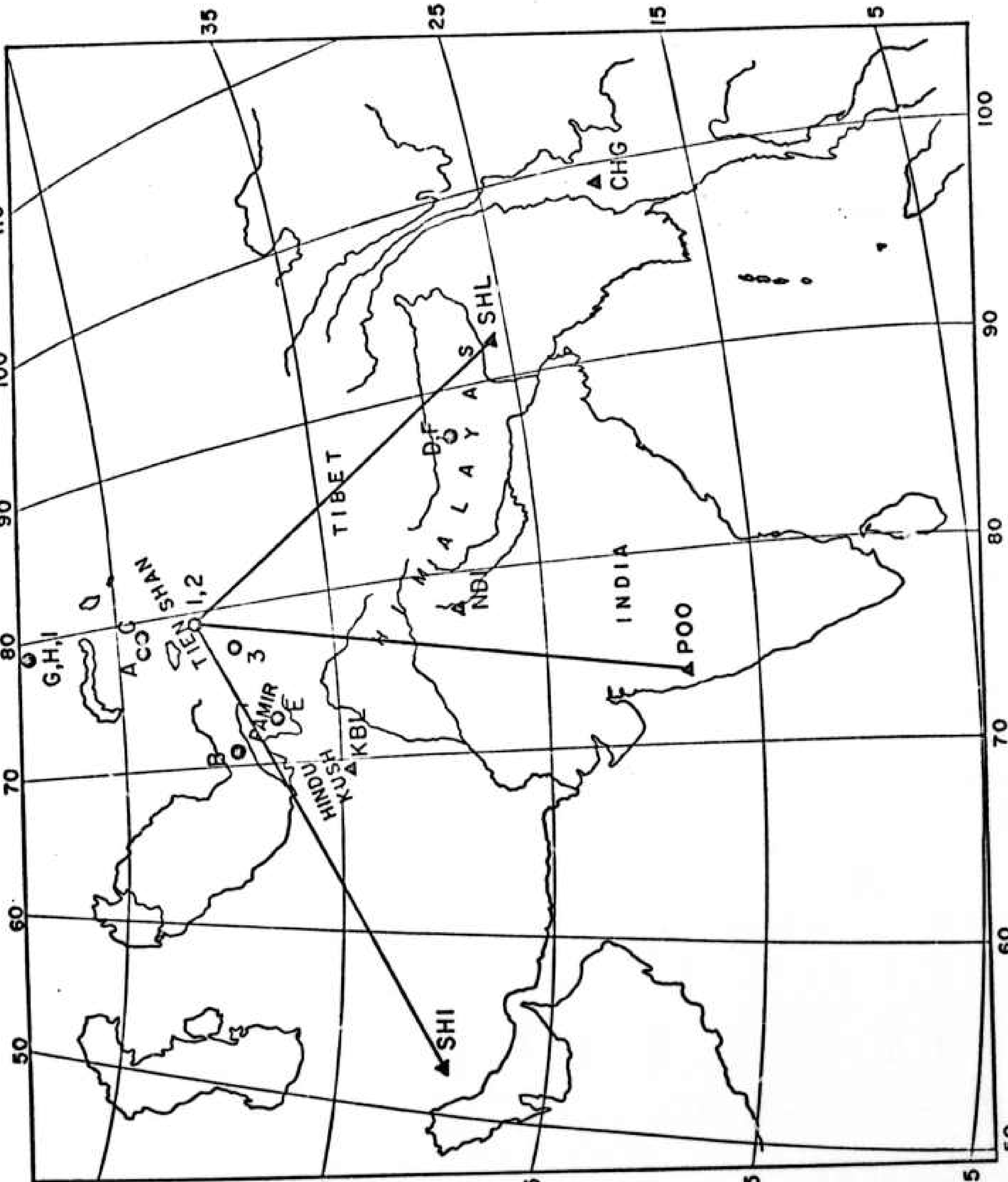

TIBET
INDIA
HINDU KUSH
PAMIR
TIEN SHAN
HIMALAYAS
SHI
KBL
NDI
POO
SHL
CHG
1,2
3
G,H,I

Figure 1.

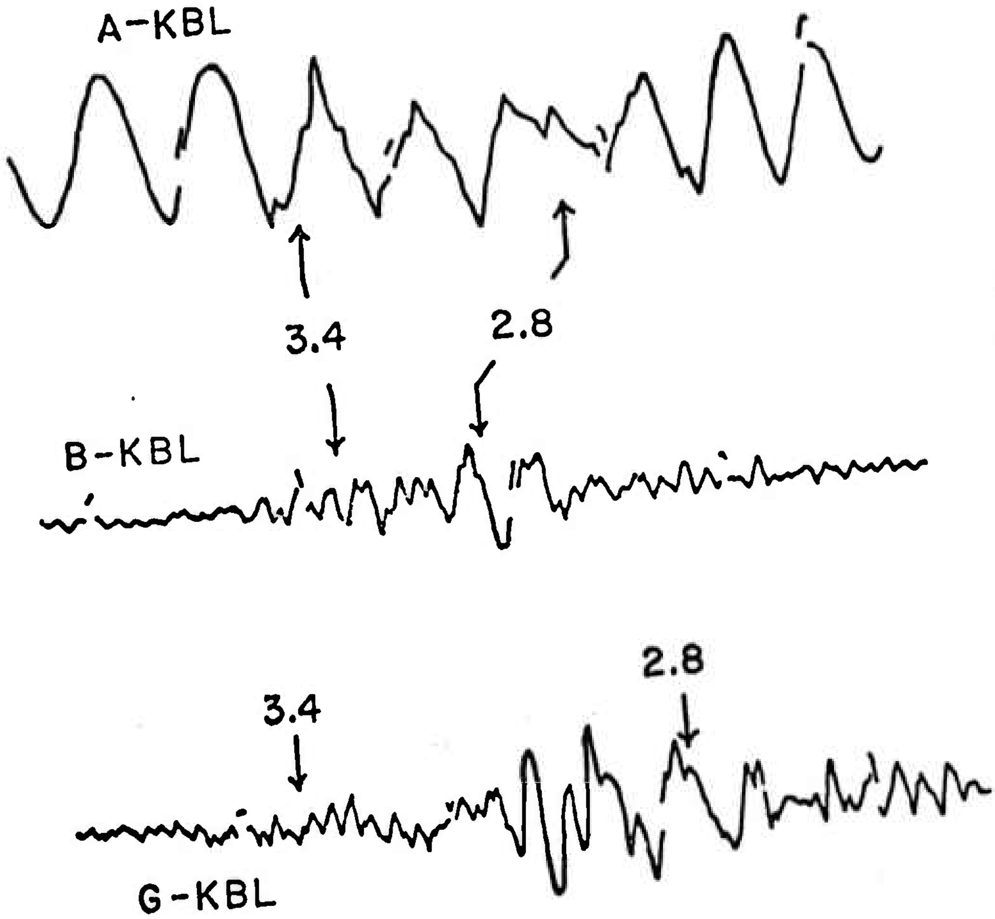


Figure 2.

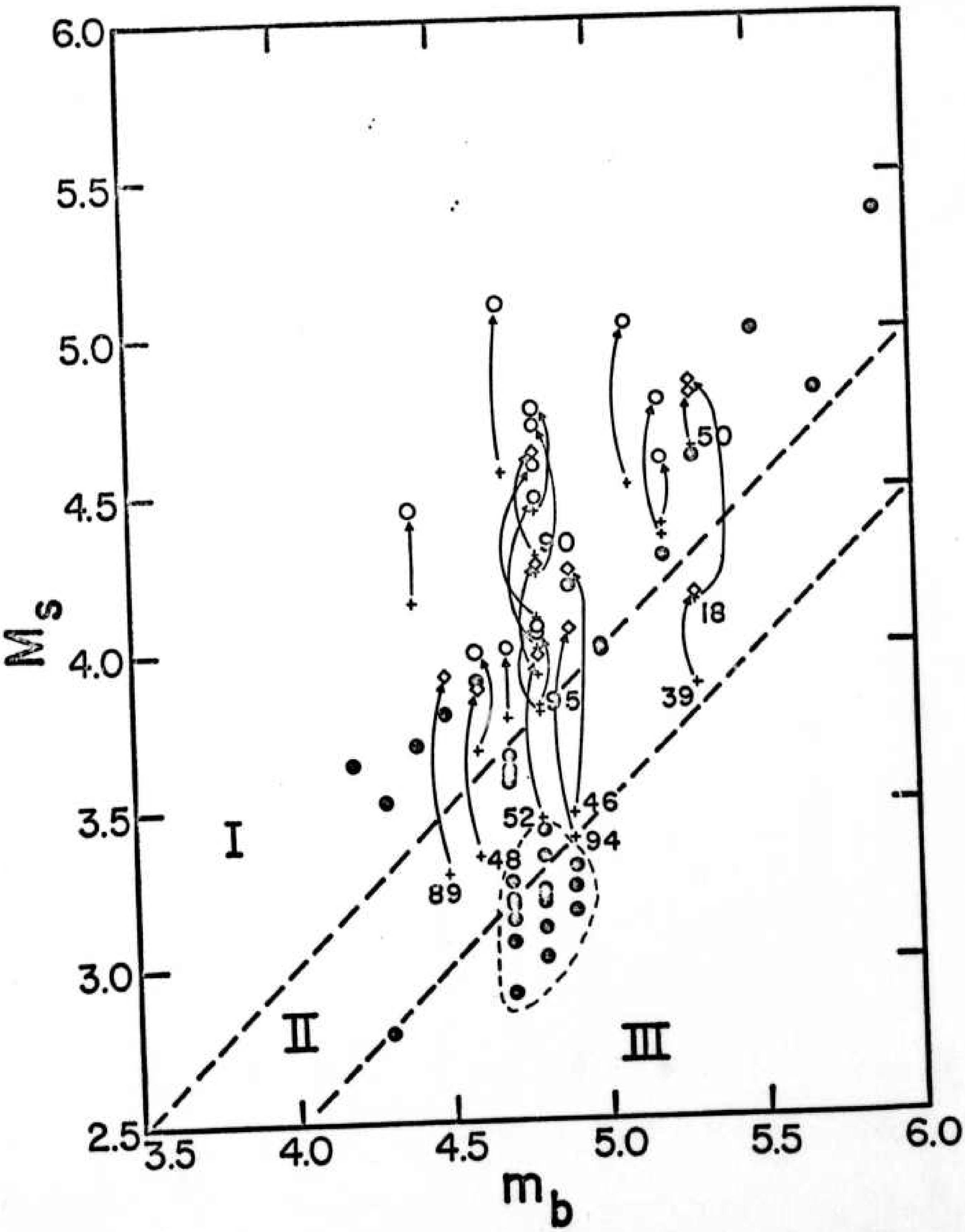

6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
M_s
3.5
4.0
4.5
5.0
5.5
6.0
m_b
I
II
III
89
48
52
46
94
95
39
18
50

Figure 3.

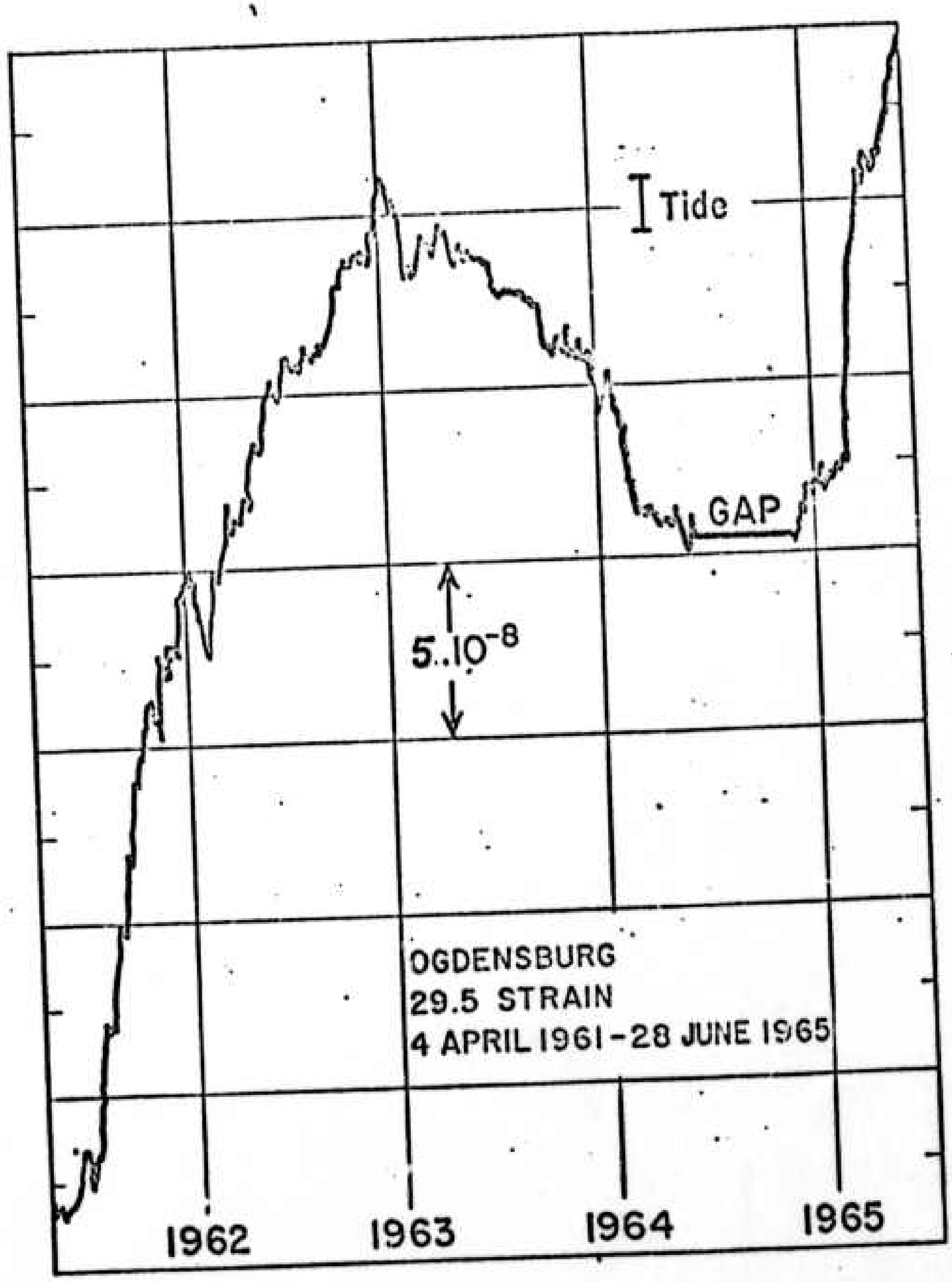

Tide
GAP
5.10^-8
OGDENSBURG
29.5 STRAIN
4 APRIL 1961 - 28 JUNE 1965
1962
1963
1964
1965

Figure 4.

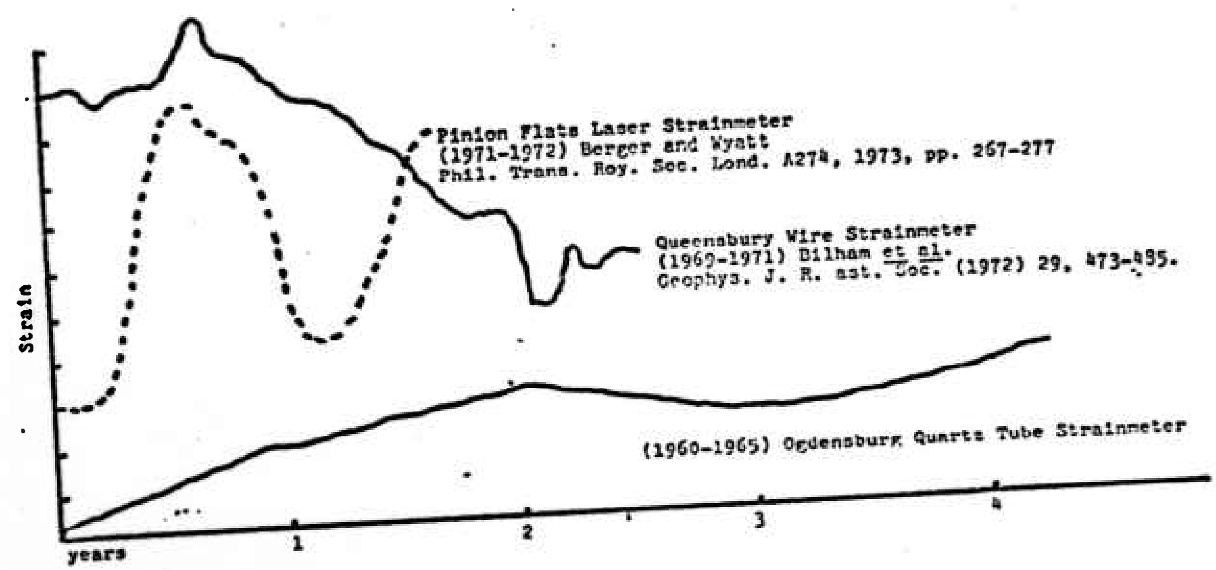
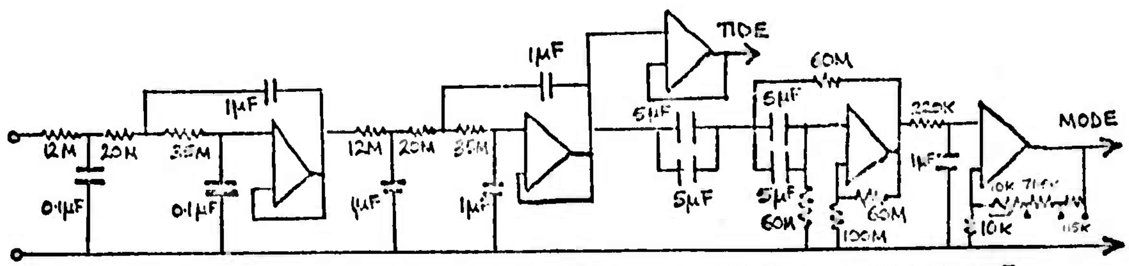
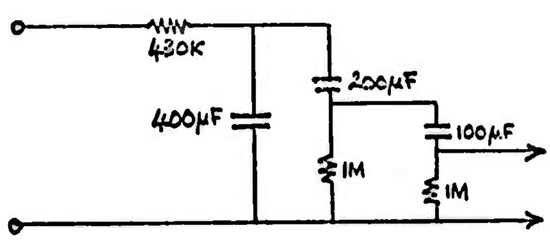

Pinion Flats Laser Strainmeter
(1971-1972) Berger and Wyatt
Phil. Trans. Roy. Soc. Lond. A274, 1973, pp. 267-277
Queensbury Wire Strainmeter
(1969-1971) Bilham et al.
Geophys. J. R. ast. Soc. (1972) 29, 473-485.
(1960-1965) Ogdensburg Quartz Tube Strainmeter
Strain
years
1
2
3
4

Figure 5.

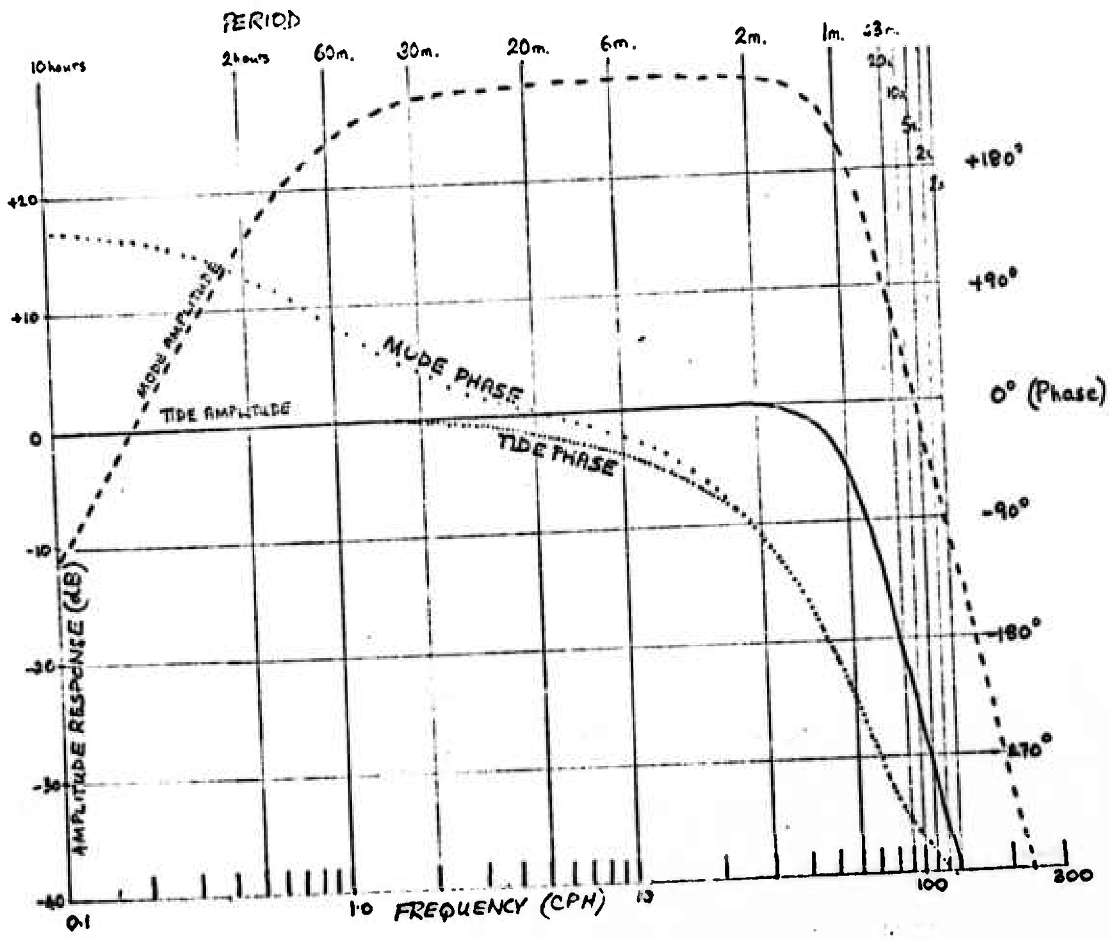


NEW FREE-OSCILLATION FILTERS (1975) [W.E.FARRELL, CIRES, BOULDER]
FOR 29.5°, 45.5°, 132° + VERTICAL STRAINMETERS
+ N/S, E/W, VERTICAL GEOTECH SEISMOMETERS (DISPLACEMENT OUTPUTS)



PREVIOUS FREE-OSCILLATION FILTER (1962-1975)

Figure 6.



PERIOD
10hours
2hours
60m.
30m.
20m.
6m.
2m.
1m.
+180°
+90°
0° (Phase)
-90°
-180°
+20
+10
0
-10
-20
-30
-40
MODE AMPLITUDE
MODE PHASE
TIDE AMPLITUDE
TIDE PHASE
AMPLITUDE RESPONSE (dB)
FREQUENCY (CPH)
0.1
1.0
10
100
300

Figure 7.

~~Unclassified (31 December 1975)~~
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